X-ray emission properties of galaxies in Abell 3128

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2 February 2008

ABSTRACT

We use archival *Chandra X-Ray Observatory* data to investigate X-ray emission from early-type galaxies in the rich $z = 0.06$ cluster Abell 3128. By combining the X-ray count-rates from an input list of optically-selected galaxies, we obtain a statistical detection of X-ray flux, unbiased by X-ray selection limits. Using 87 galaxies with reliable *Chandra* data, X-ray emission is detected for galaxies down to $M_B \approx -19.0$, with only an upper limit determined for galaxies at $M_B \approx -18.3$. The ratio of X-ray to optical luminosities is consistent with recent determinations of the low-mass X-ray binary content of nearby elliptical galaxies. Taken individually, in contrast, we detect significant (3σ) flux for only six galaxies. Of these, one is a foreground galaxy, while two are optically-faint galaxies with X-ray hardness ratios characteristic of active galactic nuclei. The remaining three detected galaxies are amongst the optically-brightest cluster members, and have softer X-ray spectra. Their X-ray flux is higher than that expected from X-ray binaries, by a factor 2–10; the excess suggests these galaxies have retained their hot gaseous haloes. The source with the highest L_X/L_B ratio is of unusual optical morphology with prominent sharp-edged shells. Notwithstanding these few exceptions, the cluster population overall exhibits X-ray properties consistent with their emission being dominated by X-ray binaries. We conclude that in rich cluster environments, interaction with the ambient intra-cluster medium acts to strip most galaxies of their hot halo gas.

Key words: galaxies: clusters: individual: Abell 3128 — galaxies: elliptical and lenticular, cD — galaxies: haloes — X-rays: galaxies

1   INTRODUCTION

Early-type galaxies emit X-rays through at least three mechanisms. Low-mass X-ray binaries (LMXBs) generate X-ray emission from an accretion disk formed around a degenerate object in close binary systems, and are likely to be present in all such galaxies. Active galactic nuclei (AGN) are certainly harboured by some galaxies, generating X-rays from accretion onto a central super-massive black hole. Finally, some systems emit copious X-rays from a gravitationally-confined halo of hot ($\sim 10^7$ K) interstellar gas.

The ratio of X-ray to optical luminosity, L_X/L_B, varies dramatically amongst early-type galaxies, spanning a range of up to two orders of magnitude between the so-called 'X-ray bright' and 'X-ray faint' classes (Canizares, Fabbiano & Trinchieri 1987). This great diversity is thought to arise mostly from the presence or absence of hot halo emission: while some galaxies have retained their interstellar medium, in others this gas has been removed, perhaps by ram-pressure stripping in galaxy clusters and groups (although other processes have been proposed). Many studies have searched for a dependence of the X-ray to optical lu-

minosity ratio, L_X/L_B on local environmental parameters, in an effort to establish the mechanism by which the haloes are lost or retained. To date however, no coherent picture has emerged, with some studies (e.g. White & Sarazin 1991) reporting supressed X-ray emission in high-density environments, while others (e.g. Brown & Bregman 2000) find increasing L_X/L_B with ambient density. In the case of galaxies which are dominant within their group or cluster, it is particularly difficult to establish whether the X-ray emission arises from the galaxy, or rather from an intra-group medium (e.g. Helsdon et al. 2001). Analysing a homogenized compilation of ROSAT data, O'Sullivan Forbes & Ponman (2001) concluded that L_X/L_B is not *systematically* dependent on environment when AGN and group- (and cluster-) dominant galaxies are discounted.

Early studies of X-ray emission from E/S0s were mostly restricted to nearby galaxies in the field, in poor groups, and in the Virgo and Fornax clusters. The densest environments, by contrast, can be probed only by studying rich galaxy clusters, which lie at much greater distances. Such studies were undertaken using ROSAT/PSPC data by Dow & White (1995) for the Coma cluster, and using ROSAT/HRI

by Sakelliou & Merrifield (1998) for Abell 2634. Both of these works employed the technique of source 'stacking' to obtain an unbiased statistical detection of X-ray flux from optically-selected galaxies.

With the advent of high-resolution X-ray astronomy made possible by the *Chandra X-Ray Observatory*, detailed studies of point-sources in cluster fields have been reported by several authors (e.g. Sun & Murray 2002; Martini et al. 2002). To our knowledge, however, there have been no published studies extending the source-stacking method to distant clusters using *Chandra* data. In this paper, we present just such an analysis, based on an archival observation of Abell 3128, a rich, highly-substructured, cluster at $z = 0.06$.

2   OBSERVATIONS AND DATA REDUCTION

2.1   Optical Imaging

The present study is based on a catalogue of galaxies detected in optical imaging from the NOAO Fundamental Plane Survey (NFPS). The NFPS is a survey of ∼100 rich low-redshift galaxy clusters, with principal science goals in the fields of large-scale structure (peculiar velocity measurements) and galaxy evolution, using stellar population diagnostics. The NFPS provides mosaic imaging data in the B and R bands, and follow-up intermediate dispersion spectroscopy for 30–90 $R < 17$ red-sequence member galaxies per cluster. For an early summary of the NFPS, see Smith et al. (2000).

The optical imaging observations of Abell 3128 were obtained in September 1999, using the 8k Mosaic camera at the Blanco 4m Telescope of the Cerro Tololo Inter-American Observatory (CTIO). Two 90 s images were obtained in B and two 60 s images in R. Reductions followed typical methods for large-format cameras, as implemented in the *mscred* package of IRAF. Objects were detected and galaxy catalogues compiled using SExtractor (Bertin & Arnouts 1996). Optical magnitudes quoted here are total (Kron-type) SExtractor magnitudes, corrected for k-dimming at the cluster redshift ($k_R = -0.06, k_B = -0.29$) and uniform galactic extinction ($A_R = 0.04, A_B = 0.07$; Schlegel, Finkbeiner & Davis 1998). The input list for X-ray flux measurements consists of all galaxies satisfying $R < 18.0$ and $B < 20.0$. Over this range the cluster exhibits a very prominent red-sequence, indicating the large fraction of passive E/S0 galaxies. The optical catalogue contains ∼250 galaxies, but of these only 104 are covered by the *Chandra* observation discussed below.

2.2   X-ray data

The *Chandra* data derive from a 20 ks observation in the ACIS-I configuration (PI J. Rose). The observation placed the cluster A3128 at the aimpoint of the ACIS-I array. The diffuse emission has been analysed by Rose et al. (2002), who discuss the 'double-peaked' morphology of the cluster in X-rays.

The data were reduced using CIAO 2.2 (and calibration data in CALDB 2.15), following standard processing 'threads'. No background flares were apparent in the light curve, so no time filters were applied. Since high angular resolution is critical for reducing contamination from the cluster background and from neighbouring sources, we consider only the four CCDs of the ACIS-I array, covering an area 15×15 arcmin.

X-ray counts were measured at positions defined by the optical galaxy catalogue, after correction for an astrometric offset of 0.7 ± 0.1 arcsec established using a handful of unambiguous bright sources. At each galaxy position, counts were summmed over the energy range 0.5-2.0 keV, in a circular 'source' aperture, and also in a concentric 'background' annulus. The source aperture radius was varied with location in the ACIS array, so as to include 99% of the local point-spread function flux, computed at an enery of 1 keV. The counts were weighted according to the exposure map, likewise computed for an energy of 1 keV, yielding a common flux system over the array. To convert count rates to fluxes in the 0.5–2.0 keV band, we assumed a thermal bremsstrahlung spectral model, with a temperature of 8.1 keV. This model is appropriate for sources dominated by LMXBs (Sarazin, Irwin & Bregman 2001). In converting to X-ray luminosity, we adopt a cosmological model with $(\Omega_m, \Omega_\Lambda, h) = (0.3, 0.7, 0.7)$, yielding a luminosity distance of 273 Mpc for z=0.060. All sources are assumed to lie at the cluster distance. Luminosities are corrected for galactic neutral hydrogen absorption with column density $n_H = 1.47 \times 10^{20}$ cm^{-2} (Dickey & Lockman 1990).

In order to improve the reliability of the photometry, we rejected sources lying in regions of high background intensity. This primarily affects galaxies in the two bright X-ray clumps at the north–east and south–west of the field (Rose et al. 2002). Furthermore, we rejected measurements in which the centroid of the background counts was significantly ($>3\sigma$) displaced from the aperture centre; this criterion is especially valuable in removing measurements where the background estimate is compromised by a bright point source. After removing these sources, the matched X-ray-optical catalogue contains flux measurements for 87 galaxies.

Strictly, these flux measurements are valid only for point sources. If the X-ray emission is distributed similarly to the stellar light (as may be approximately the case for LMXBs), then this assumption slightly underestimates the total flux. Based on measured half-light radii, the typical aperture correction is $\Delta \log L_X \approx 0.04$, while ∼6 galaxies would require corrections of $\Delta \log L_X = 0.15 - 0.22$.

The above procedure was also applied to measure counts in a harder energy range (2.0-10.0 keV). For this case, we applied exposure map and point-spread function estimates appropriate for a 6 keV mono-energetic source.

3   RESULTS

3.1   Individually-detected sources

Figure 1 shows the $B - R$ colour–magnitude relation for the input catalogue galaxies, highlighting those objects with significant ($> 3\sigma$) X-ray detections. The properties of these sources are also summarized in Table 1.

The six detected sources fall into two apparent groups in colour-magnitude space. The first group contains four of the brightest galaxies on (and redwards of) the E/S0 sequence. These objects are detected with high significance in
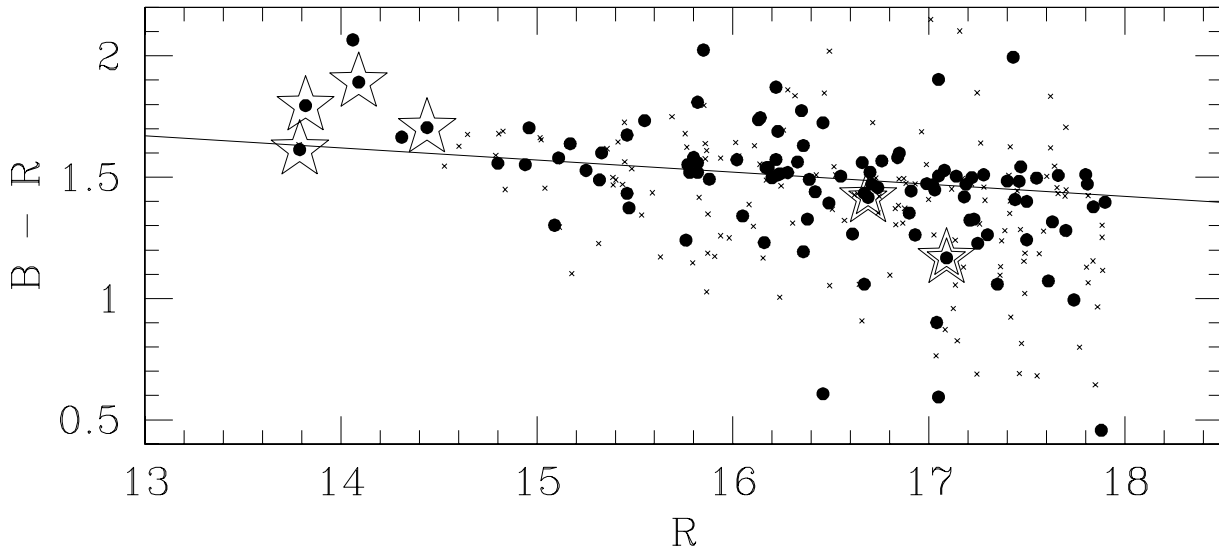
Figure 1. Optical $(B-R)$ colour–magnitude relation for NFPS sample galaxies in Abell 3128. Filled circles mark galaxies with overlapping X-ray data, while small crosses represent galaxies outside of the *Chandra* field of view, or with unreliable X-ray data (see text). Large stars mark galaxies with significant X-ray flux detections at 0.5–2.0 keV (the brightest of these is actually a foreground galaxy). Those with 'double' stars are also detected in the 2.0–10.0 keV band, and are probably AGN.

the 0.5–2.0 keV band, but only marginally in the hard (2.0-10.0 keV) band. In fact, Source 1 is a foreground object with $z = 0.039$ (Katgert et al. 1998). The other three optically-bright sources are confirmed cluster members. The X-ray emission from Sources 2 and 4 is twice that expected from LMXBs (see below). Source 3 outshines the LMXB predictions by a factor $\sim$10. Interestingly, this galaxy lies close to the North–East peak of the cluster emission (Rose et al. 2002), but not coincident with it. The NFPS spectrum of this source suggests a quiescent giant elliptical, but the morphology is unusual: the galaxy has an extended sharp-edged outer shell or envelope. It is tempting, given these cD-like characteristics, to identify Source 3 as the former dominant galaxy of an infalling subcluster. However, the heliocentric recession velocity of this galaxy, from the NFPS spectrum, is $17241 \, \mathrm{km\,s^{-1}}$, which is not consistent with the redshift-space group suggested by Rose et al. to be associated with the North–East X-ray peak ($cz =$18600–19400 $\mathrm{km\,s^{-1}}$).

The remaining two X-ray sources (5 and 6) are optically much fainter, and lie on the blue side of the CMR. The redshifts of these sources are not known. In addition to their soft emission, these galaxies were also detected at high significance ($> 3\sigma$) in the hard bandpass. Given the hard-to-soft flux ratios and high luminosities of these sources, we consider it likely that X-ray emission in these galaxies arises primarily from AGN activity. If these are cluster members, the AGN fraction amongst the sample galaxies is $\sim$2.5%, subject of course to very large uncertainties. This may be compared with recent *Chandra* estimates of $\sim$ 5% for Abell 2104 (Martini et al. 2002) and $\sim$12% for Abell 1367 (Sun & Murray 2002). Selecting by optical spectroscopy yields an AGN fraction of $\sim$1% in clusters (Dressler et al. 1999), but misses low-luminosity or heavily obscured sources.

3.2 Stacked-source results

For the purpose of combining fluxes for galaxies grouped by luminosity, we exclude the two galaxies with strong hard X-ray fluxes (whether AGN or not, these clearly do not belong to the general population of cluster galaxies). In addition, of course, the criteria already mentioned are used to reject galaxies in regions of high diffuse X-ray emission, and those with asymmetric backgrounds.

The mean stacked-source fluxes and their errors are computed in four bins of B-band luminosity, as shown in Figure 2. Only an upper limit is obtained for the faintest luminosity bin. Also shown in this figure are estimates of the LMXB contribution, scaling from the LMXB population observed in nearby ellipticals. The upper line is based on the results of Sarazin et al. (2001), who estimated the total flux from LMXBs in the nearby X-ray faint elliptical NGC 4697, yielding $L_{\mathrm{LMXB}}(0.3-10\,\mathrm{keV})/L_B = 8.1 \times 10^{29} \, \mathrm{erg\,s^{-1}} \, L_\odot^{-1}$. Similar values have been obtained for NGC 720 (Jeltema et al. 2003) and NGC 1553 (Blanton, Sarazin & Irwin 2001). In the absence of a wider study employing consistent source detection and analysis conventions, it is difficult to generalize these results or estimate the intrinsic distribution of LMXB-to-optical luminosity ratio. From an unpublished compilation, White, Sarazin & Kulkarni (2002) claim a factor of four variation in this ratio; there is evidence that many LMXBs are created in globular clusters, so that their contribution may depend on cluster frequency (White et al. 2002; Kundu, Maccarone & Zepf 2002). To reflect the uncertain range, we simply set the lower line in Figure 2 to a factor of three lower than that of NGC 4697. In calculating the LMXB predictions for the bandpass adopted here, we model the LMXB emission using a 8.1 keV thermal bremsstrahlung spectrum (the best-fitting model of Sarazin et al.).

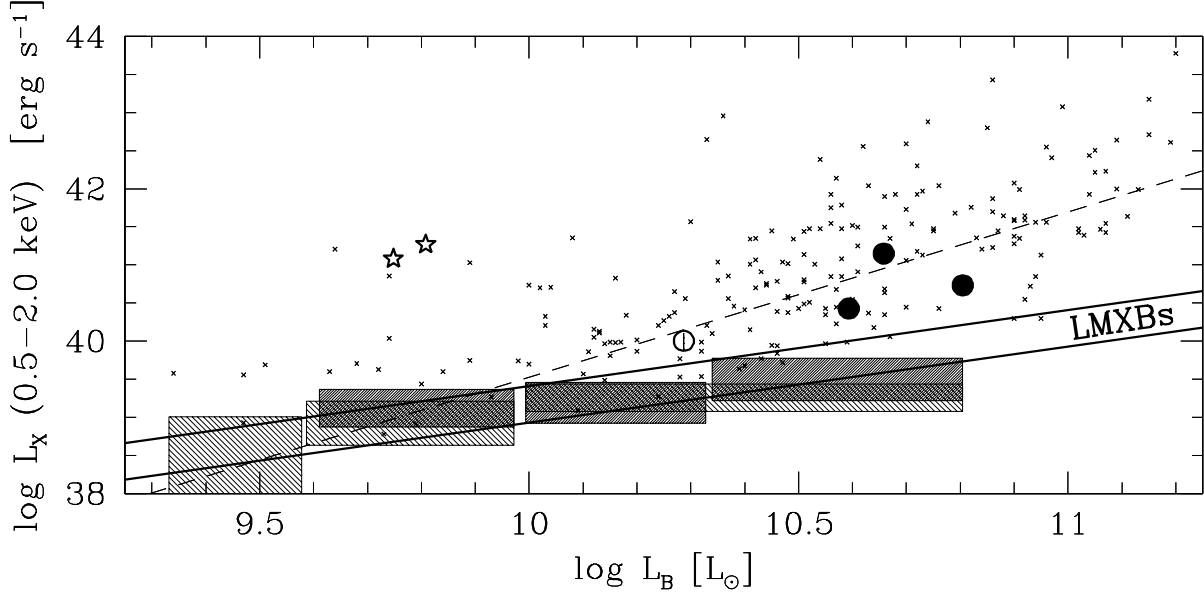The small points in Figure 2 represent X-ray detected

Figure 2. X-ray luminosities from stacked sources, computed over four bins in B-band luminosity. The large symbols show the four galaxies with significant detections: filled circles are confirmed cluster members, the open circle is a known foreground galaxy (luminosities computed for the true redshift). The two open stars indicate the probable AGN, with luminosities computed as if they were at the cluster redshift. The shaded boxes show the mean X-ray luminosity in each bin, with the vertical extent indicating the error (only an upper limit is obtained for the faintest bin). The horizontal extent of the box indicates the luminosity range of galaxies in the bin. The dark-shaded boxes show results for confirmed cluster members only, with 'aperture' corrections applied. Two solid lines of unit slope indicate the expected trend if LMXBs dominate the X-ray emission. Finally, the small points and dashed line represent the detections of O'Sullivan et al. (2001), together with their bias-corrected fit.

Table 1. Abell 3128 galaxies detected at $> 3\sigma$ in the 0.5–2.0 keV band.

ID	R.A. [J2000]	Dec	R [mag]	$B - R$ [mag]	L_X [0.5–2.0 keV] [$10^{40}\,\mathrm{erg\,s^{-1}}$]	Notes
1	03:29:53.125	−52:30:54.70	13.79	1.614	0.8±0.2	Foreground object z=0.039
2	03:30:38.429	−52:37:09.64	13.82	1.795	4.1±0.9	Normal E/S0
3	03:30:51.032	−52:30:31.32	14.09	1.892	10.7±1.5	E/S0 with shells
4	03:30:13.684	−52:37:30.04	14.44	1.704	2.0±0.6	Normal E/S0
5	03:30:17.322	−52:34:08.72	16.69	1.417	14.0±1.6	Hard spectrum : AGN?
6	03:29:41.460	−52:29:36.01	17.09	1.167	9.1±1.3	Hard spectrum : AGN?

Note: Luminosities computed assuming the cluster distance except for source #1

galaxies in the ROSAT compilation of O'Sullivan et al. (2001). Their fit (dashed line) is based on a survival-statistics analysis of these detections, together with upper limits not shown here. There is a striking difference between the ROSAT sample and our data for Abell 3128: at the bright end, our stacked-source measurements lie a factor of ∼20 fainter in X-rays than the O'Sullivan et al. sample. The steep slope of the ROSAT sample is not reproduced here; rather, the slope is consistent with direct proportionality with the optical luminosity. Finally, the overall zero-point of the $L_X - L_B$ relationship is, for our sample, fully consistent with the contribution expected from LMXBs alone. These results argue strongly that, at least in the very richest environments, most cluster galaxies are indeed deprived of their hot X-ray haloes.

We have assumed in these calculations that all NFPS galaxies lie at the cluster distance. Where cluster membership can be confirmed using NFPS spectra and literature data (via NED), similar results are obtained, differing only in the last bin where no redshifts are available. Figure 2 shows, as dark shaded boxes, the results for confirmed cluster members. In addition, these latter points are corrected for source-extension based on the measured half-light radius, as discussed above. It is seen that these corrections are very small in comparison to the size of the observed effect. To test the assumption that early-type galaxies dominate the sample, a two-dimensional profile-fitting code (GIM2D: see Simard et al. 2002) was used to identify ∼20 galaxies with small bulge-to-disk ratios. Removing these galaxies has little effect on the results.

4 DISCUSSION

The principal result of this *Letter* is that the X-ray emission from cluster members can be accounted for by the LMXB population alone. With the probable exception of the ~ 3 galaxies noted in the previous section, galaxies in this very rich cluster do not show signs of emission from haloes of hot gas. This result can be interpreted as evidence for a strong environmental influence on the X-ray properties, with gas haloes being removed from cluster galaxies through, for example, ram-pressure stripping by the intra-cluster medium (White & Sarazin 1991).

Our result is qualitatively similar to that of Sakelliou & Merrifield (1998), who applied a similar method to high-spatial resolution ROSAT/HRI data for Abell 2634, concluding that LMXBs account for the entirety of the emission. Similarly, an earlier application of the source-stacking technique to Coma, by Dow & White (1995), found X-ray luminosities compatible with LMXBs, at least for the fainter galaxies in their sample. (The brightest galaxies are coincident with enhancements in the diffuse cluster gas, from which they cannot be unambiguously separated in their ROSAT/PSPC observation.)

This apparently consistent picture from studies using source-stacking contrasts starkly with the inconclusive results of 'compiled' galaxy samples. For example, White & Sarazin (1991) claimed that X-ray bright ellipticals have fewer neighbours than their X-ray faint cousins (a result which argues in the same sense as ours), while O'Sullivan et al. (2001) have concluded that no coherent environmental mechanism drives the enormous range in L_X/L_B. Brown & Bregman (2000) claim a contrary result, with L_X/L_B increasing with density.

It seems probable that this confused picture arises partly from difficulties in disentangling galaxy emission from that of a surrounding group or cluster (Helsdon et al. 2001). The 'compiled' samples moreover contain very few galaxies in extremely rich (Coma-like) clusters, and those which are included are typically the brightest cluster members. The source-stacking method applied to clusters has the advantage of probing 'typical' early-type galaxies in the very environments where stripping is likely to be most efficient.

5 CONCLUSIONS

Our X-ray source-stacking analysis of of E/S0 galaxies in Abell 3128 demonstrates that the cluster population is dominated by 'X-ray faint' objects, with typical X-ray to optical flux-ratio ~ 20 times smaller than typical for field/group samples. Similar results have previously been obtained for Coma and Abell 2634. The natural explanation is in terms of a greater tendency for stripping of gas haloes in the densest environments.

Excluding probable AGN, only one detected cluster member is as X-ray luminous as a typical field/group elliptical. It has an unusual optical morphology with an outer shell or envelope. Two further bright galaxies have emission in somewhat in excess of the LMXB predictions.

The data presented here thus yield a mixed picture in which most galaxies are stripped, but just a few apparently retain a hot halo. The distribution and properties of the latter should provide insights into the mechanisms which drive this dichotomy, but more cases are clearly required. We are currently applying the source-stacking analysis to a larger number of clusters, which will provide a sample large enough for meaningful comparisons between galaxies of morphological classes and in clusters of differing richness.

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